

Naval Research Laboratory

Washington, DC 20375-5320



NRL/MR/6180--03-8708

A Methodology for Predicting Fire and Smoke Spread Following a Weapon Hit

GERARD G. BACK

ERIN C. MACK

MICHELLE J. PEATROSS

JOSEPH L. SCHEFFEY

DEREK A. WHITE

*Hughes Associates, Inc.
Baltimore, MD*

JOHN P. FARLEY

FREDERICK W. WILLIAMS

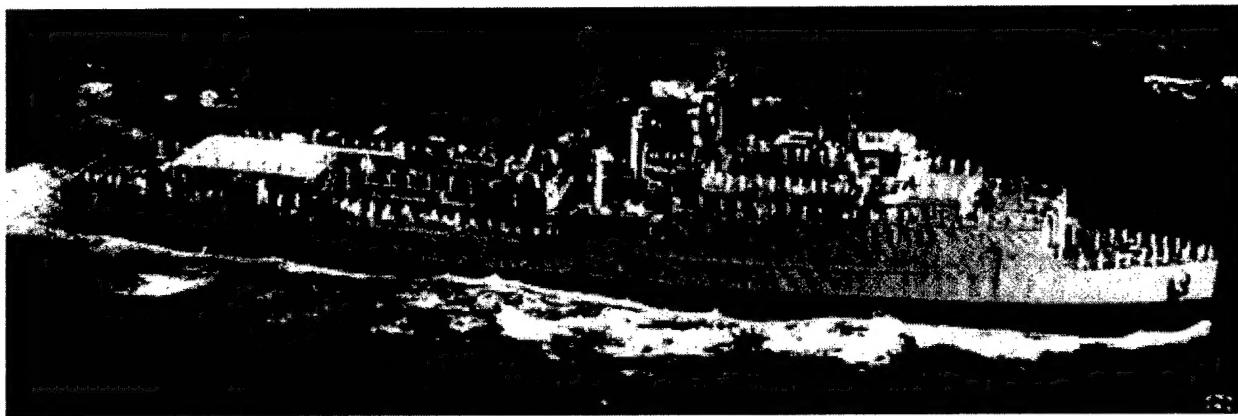
*Navy Technology Center for Safety and Survivability
Chemistry Division*

DAVID SATTERFIELD

*Naval Sea Systems Command
Code 05P4*

September 30, 2003

20031010 047



Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) September 30, 2003	2. REPORT TYPE Memorandum Report	3. DATES COVERED (From - To) January 1, 2002-December 30, 2002		
4. TITLE AND SUBTITLE A Methodology for Predicting Fire and Smoke Spread Following a Weapon Hit		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Gerard G. Back,* Erin C. Mack,* Michelle J. Peatross,* Joseph L. Scheffey,* Derek A. White,* John P. Farley, Frederick W. Williams, and David Satterfield†		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory, Code 6180 4555 Overlook Avenue, SW Washington, DC 20375-5320		8. PERFORMING ORGANIZATION REPORT NUMBER NRL/MR/6180-03-8708		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Sea Systems Command 1333 Isaac Hull Avenue, SE Washington Navy Yard, DC 20376		10. SPONSOR / MONITOR'S ACRONYM(S)		
		11. SPONSOR / MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.				
13. SUPPLEMENTARY NOTES *Hughes Associates, Inc., 3610 Commerce Drive, Suite 817, Baltimore, MD 21227 †Naval Sea Systems Command, Code 05P4, 1333 Isaac Hull Avenue, Washington Navy Yard, DC 20376				
14. ABSTRACT A methodology has been developed as part of a congressionally mandated LFT&E program to predict smoke and fire spread after a weapon hit. The objective of the current methodology is to identify specific weaknesses and/or shortcomings that might increase survivability. The process involves modeling PDA(F) compartments with the multi-compartment zone fire model CFAST. The use of CFAST allows for a more complete characterization of these compartments. The output from CFAST is used to predict fire spread times and assess tenability conditions. Fire spread beyond these compartments to APDA(F) and BAPDA(F) compartments is predicted using a conservative set of perspective rules.				
15. SUBJECT TERMS Fire; Model; Smoke; Damage control				
16. SECURITY CLASSIFICATION OF: a. REPORT Unclassified		17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 36	19a. NAME OF RESPONSIBLE PERSON Frederick W. Williams
b. ABSTRACT Unclassified				19b. TELEPHONE NUMBER (include area code) 202-767-2476

CONTENTS

1.0	INTRODUCTION.....	1
2.0	APPROACH.....	1
3.0	METHODOLOGY.....	5
4.0	SUMMARY.....	20
5.0	FUTURE DEVELOPMENTS.....	26
6.0	REFERENCES.....	29

ACRONYMS AND NOMENCLATURE

APDA	Adjacent to Primary Damage Area
APDA(F)	Adjacent to Primary Damage Area for Fire & Smoke Spread
ASAP	Advanced Survivability Assessment Program
ASTM	American Society for Testing and Materials
BAPDA	Beyond Adjacent to Primary Damage Area
BAPDA(F)	Beyond Adjacent to Primary Damage Area for Fire & Smoke Spread
BDRA	Battle Damage Repair Assessment
CFAST	Consolidated Model of Fire Growth and Smoke Transport
CVNX	The next generation aircraft carrier
DC	Damage Control
DC-ARM	Damage Control Automation for Reduced Manning
FFE	Firefighting Ensemble
HEATING	Finite difference heat conduction model
HVAC	Heating, Ventilation and Air Conditioning
ISCC	Internal Ship Conflagration Control
LFT&E	Live Fire Testing and Evaluation
LPD 17	Amphibious transport dock
NIST	National Institute of Standard and Technology
NRL	Naval Research Laboratory
NSWC/CD	Naval Surface Warfare Center, Carderock Division
PDA	Primary Damage Area
PDA(F)	Primary Damage Area for Fire & Smoke Spread
SCBA	Self Contained Breathing Apparatus
SVM	Ship Vulnerability Model
TSS	Total Ship Survivability
VAR	Vulnerability Assessment Report
VC	Vital Component
V&V	Verification and Validation
VV&A	Verification, Validation and Accreditation
WR/WC/SH	Washrooms, Water Closets and Showers
WET	Weapons Effects Test

A METHODOLOGY FOR PREDICTING FIRE AND SMOKE SPREAD FOLLOWING A WEAPON HIT

1.0 INTRODUCTION

A methodology has been developed and refined to predict smoke and fire spread after a weapon hit. This methodology was developed to comply with the congressionally mandated Live Fire Testing and Evaluation (LFT&E) program. Under the LFT&E program for each ship platform, a vulnerability assessment is undertaken and a Vulnerability Assessment Report (VAR) is prepared. The VAR provides an evaluation of the survivability of the ship platform and ship mission against simulated weapon threats. The vulnerability assessment process includes the simulation of weapon damage, characterization of secondary damage (e.g., flooding, fire and smoke), and description of the battle damage repair activities and effectiveness. These activities are generally referred to as a Total Ship Survivability (TSS) and Battle Damage Repair Assessment (BDRA). The overall objective of the TSS/BDRA is to identify specific weaknesses and/or shortcomings as well as high payoff research and development efforts that might increase the survivability of the particular ship platform.

The current TSS/BDRA process involves consideration of various weapon hits. For each specific weapon threat scenario (shot line), the initial damage is identified by utilizing a blast damage model. Secondary damage, such as fire and smoke spread that results from the blast damage, must also be characterized. The methodology described in this document outlines the framework through which a conservative estimate of the secondary fire and smoke damage can be established. This document also uses a refined set of definitions for fire and smoke spread in damaged areas of the ship.

2.0 APPROACH

The current approach for the characterization of secondary damage associated with a weapon hit has evolved over several TSS/BDRA evaluations. The genesis of the current methodology was rudimentary fire spread times, developed by the Naval Research Laboratory

(NRL) and Hughes Associates, Inc. based on USS *Stark* incident data and testing [1]. This information was implemented in a TSS model developed by the Naval Surface Warfare Center, Carderock Division (NSWC/CD). The fire spread methodology was improved and the framework was expanded to allow for smoke spread during the evaluation performed for the LPD 17 VAR 2 [2]. Most recently, the methodology was further refined during the CVNX assessment [3]. This report reflects the most current methodology used for the CVNX assessment. The framework incorporates a combination of computer fire modeling using the Consolidated Model of Fire Growth and Smoke Transport (CFAST) program and prescriptive rules for fire spread. CFAST is specifically used to characterize the environment in the primary damage area which includes vent connected spaces.

Estimates of the worst plausible fire spread scenario for each hit are used to determine the extent of damage control (DC) operations that are required to control and secure the fire. As part of this conservative assessment framework, the effects of fixed fire suppression systems or manual firefighter activities normally associated with DC operations are **not considered** in the initial secondary damage assessment. In some instances, intact suppression systems may be evaluated on a case by case basis. Estimates of the rate of smoke production, extent of smoke migration and the temperature of the smoke layer are used to identify the potential exposures to shipboard equipment, personnel and DC parties.

Describing the methodology for predicting fire and smoke spread requires an understanding of the shipboard damage zones developed for these evaluations. The zones are categorized in three ways:

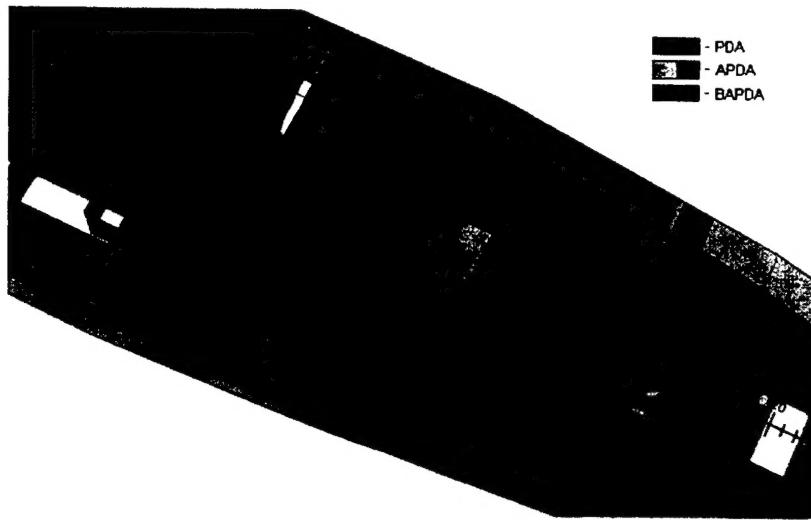
Primary Damage Area (PDA) compartments: PDA compartments are those that incur significant damage from the weapon hit (e.g., failed deck/bulkhead and shock holing). **It should be noted that compartments that are only vent connected to PDA compartments as a result of door/hatch failure have not been considered part of the PDA in certain contexts.** This definition differs from that used in Damage Control Automation for Reduced Manning (DC-ARM) testing [4-6] and Weapons Effect Test (WET) for the ex-*Caron* fire and smoke spread [7], where all compartments that are vent

connected as a result of the blast damage are considered PDA compartments. From the standpoint of fire and smoke spread, including the vent connected spaces makes more sense. This is due to the fact that the vents provide a means for spreading fire and smoke directly as well as supplying additional oxygen for the fires. **Therefore, in the future we recommend designating the fire and smoke spread PDA (noted as PDA(F)) where vent connected spaces are included.**

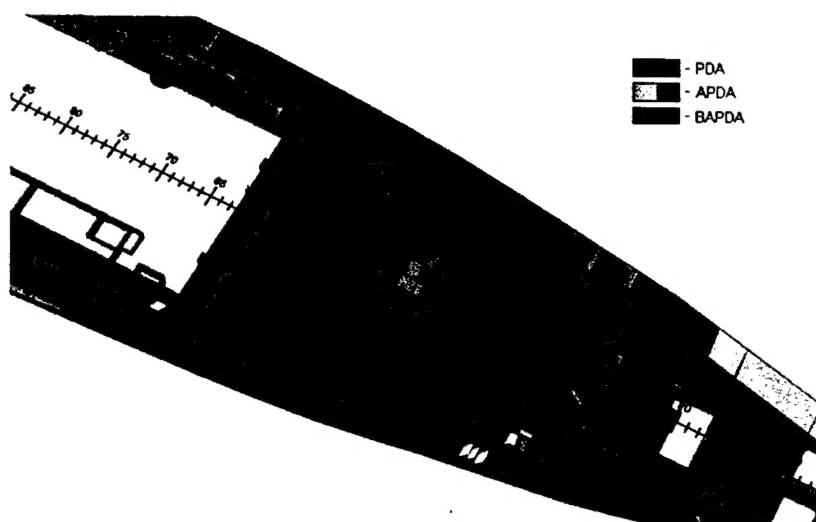
Adjacent to Primary Damage Area (APDA) compartments: These compartments share a common boundary (bulkhead, overhead or deck) with a PDA compartment. Historically these compartments included spaces with a communicable opening (e.g., vent connection) between PDA compartments and the APDA compartment, such as a failed door or hatch. Our recommended definition for fire and smoke spread for adjacent compartments, APDA(F), excludes any compartments that have vent openings to the PDA. This is a result of those vented compartments becoming part of the PDA(F).

Beyond Adjacent to Primary Damage Area (BAPDA) compartments: These compartments border APDA spaces. They can be otherwise described as “twice removed” from the PDA. These spaces may be a concern due to potential fire spread later into the event. It is typically assumed that there are no communicable openings (i.e., vents, ducts, open doors or open hatches) between BAPDA and APDA spaces. This definition for BAPDA(F) remains the same for fire and smoke concerns as weapon effect concerns.

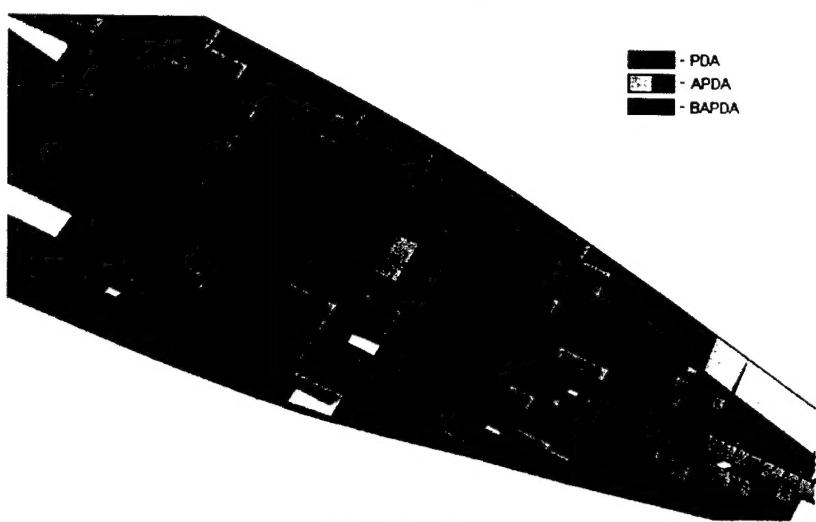
For illustrative purposes, Figure 1 shows an example of the compartment categorization of spaces for a hypothetical weapon hit using the PDA, APDA and BAPDA definitions (as compared to PDA(F), APDA(F) and BAPDA(F)). As indicated in the legend, PDA compartments are marked in red, APDA compartments are marked in yellow and BAPDA compartments are marked in blue. The PDA consists of those compartments that are structurally affected by the blast overpressure. The APDA compartments on the Third Deck and First Platform are horizontally adjacent to the PDA on those decks. In addition, there are APDA



Second Deck



Third Deck



First Platform

Figure 1. Example of compartment damage characterization after hypothetical weapon hit using PDA, APDA and BAPDA compartment designations

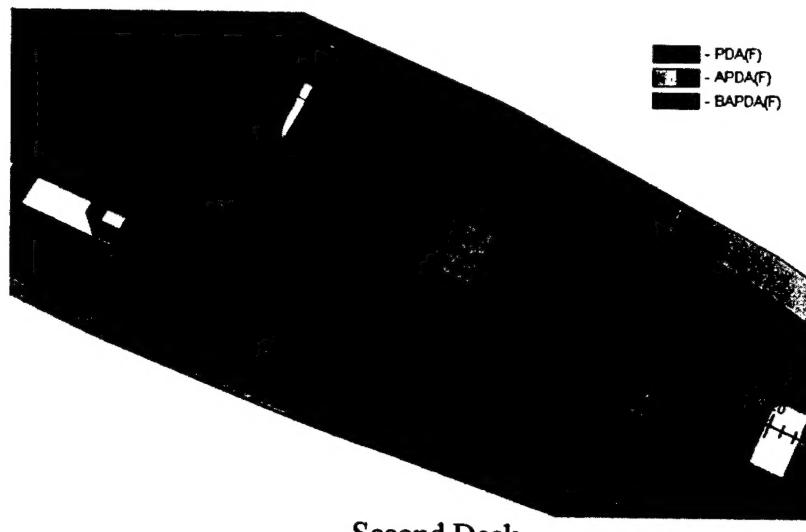
compartments on the Second Deck directly over the PDA compartments on the Third Deck. The BAPDA compartments are either horizontally adjacent to or above or below APDA compartments.

Figure 2 shows how changing the definition of the PDA, APDA and BAPDA to PDA(F), APDA(F) and BAPDA(F) would affect the definition of spaces. Irrespective of the terminology, vent connected spaces have always been included (and will continue to be included) in the fire model used to assess the spread of smoke and fire associated with the fires that start immediately following the weapon detonation. As a result, the definitions used for PDA and APDA spaces will not impact the results that are obtained from the analysis. **From this point forward, the recommended definitions for PDA(F), APDA(F) and BAPDA(F) are used in this methodology report.**

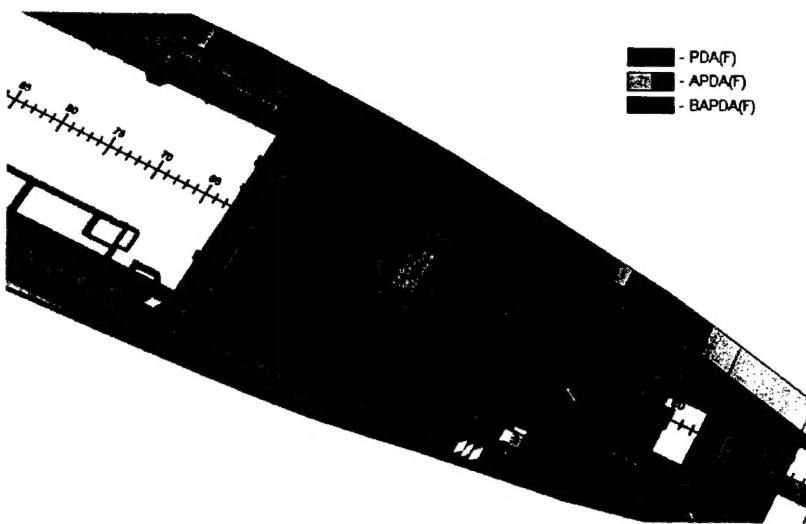
3.0 METHODOLOGY

The methodology for predicting fire and smoke spread follows the steps listed below. Each process is described in further detail in the following sections.

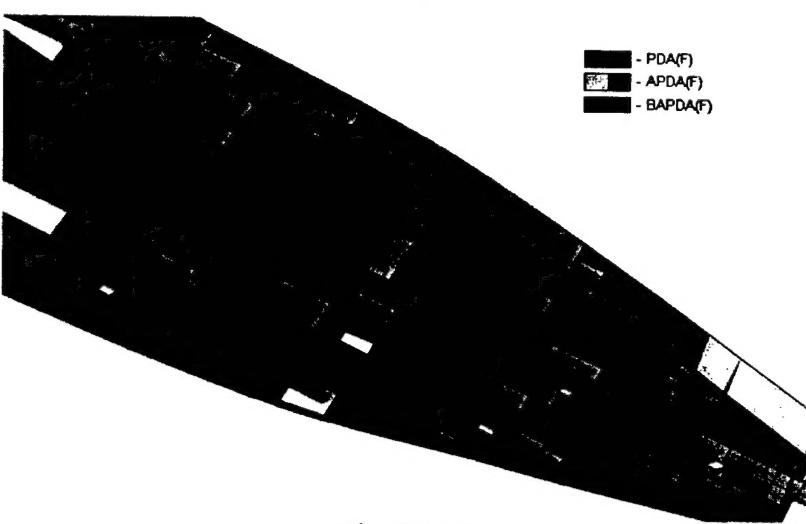
1. Establish the primary damage;
2. Review the primary damage information;
3. Characterize the secondary damage (fire and smoke spread) in the PDA(F);
4. Characterize the secondary damage to PDA(F) spaces;
5. Characterize the secondary damage to APDA(F) and BAPDA(F) compartments; and
6. Document the time dependent secondary damage estimates in snapshot format.



Second Deck



Third Deck



First Platform

Figure 2. Example of compartment damage characterization after hypothetical weapon hit using PDA(F), APDA(F) and BAPDA(F) compartment designations

3.1 Establishment of the PDA(F)

The primary damage from the weapon hit is established based on output from either the Ship Survivability Model (SVM) or the Advanced Survivability Assessment Program (ASAP) model [8, 9]. Both models are designed to simulate initial ship damage from a weapons attack. The output from either model provides information such as the locations of failed bulkheads and decks, shock holing, failed doors and hatches, overpressures, bulkhead and deck deflection, fragment damage to vital components (VCs) and damage to distributive systems. Equipment specific damage as a result of thermal or smoke exposures during the detonation and burning of the residual fuel from the weapon is not specifically included in this methodology.

The output from the ASAP or SVM model is used to establish the location of PDA(F), APDA(F) and BAPDA(F) compartments. Since the blast damage models do not provide the output in terms of PDA, APDA and BAPDA or PDA(F), PADA(F) and BAPDA(F), the characterization of space type is done as part of the fire and smoke damage assessment. Based on the model output provided, PDA(F) compartments consist of those compartments where bulkheads or decks have failed, or where shock holing has occurred. In addition, PDA(F) spaces include those compartments that are vent-connected. Vent connections may consist of failed doors or hatches, or openings created by shock holing. The structural damage incurred from a weapon detonation is translated into ventilation opening sizes based on advice from NSWC/CD Code 665. For shock holing, it is assumed that the area can be treated as a single opening with an area equivalent to 100% of the shock holing value.

In addition, it is assumed that the fire insulation attached to boundaries that experience less than a specific amount of deflection (as reported in Reference 2) remains intact and performs to specifications. For deflections greater than this value, the boundary is modeled as a bare steel bulkhead or deck.

3.2 Review of Primary Damage Information

The assumptions for each assessment consist of general assumptions that apply for each analysis and those that are specific to the hit (shot line). General assumptions include the following:

- The ship is at general quarters prior to each hit (e.g., material condition ZEBRA is set throughout the ship). This assumption implies that all ZEBRA doors, hatches and fittings are closed.
- Unless otherwise stated, heating, ventilation and air conditioning systems (HVAC) are not considered. Engineering judgment can be used in specific instances to account for the effects associated with failure of ventilation ducts. In some cases, such as with smoke ejection systems, these HVAC systems may help mitigate smoke spread or accumulation;
- For compartments that contain combustible materials, the fuel load is considered as sufficient to support post flashover fires during the evaluation;
- Thermally thin combustible materials (i.e., readily ignitable) are located such that fire spread may occur across an intact boundary. These materials may normally be in this arrangement or may be redistributed against bulkheads and decks as a result of the shock impact or over pressure;
- Transient opening and closing of doors and hatches between compartments is not considered (from people exiting the area or investigators performing an assessment);
- The weapon hit precipitates ignition in all PDA(F) spaces that are intimate with compartment containing the point of detonation and that have a combustible fuel load (due to unspent propellant or hot fragments); a fire growth rate curve is

followed for the specific fuel load. The oxygen concentration in the space could have considerable affect on the fire growth curve;

- Toxicity issues related to unspent missile propellant are not considered;
- Generally, firefighting activities and fire mitigation effects are not considered;
- For compartments that are not included in the fire model (APDA(F) and BAPDA(F) spaces), smoke production or accumulation is not characterized. Rather, it is assumed that these spaces become untenable for unprotected personnel once fire spreads to them; and
- The fuel load and air supply in APDA(F) and BAPDA(F) compartments are not considered. Rather, it is assumed that there is a sufficient quantity of fuel and air to support flashover conditions. In reality, these compartments would not necessarily become fully involved, particularly if they are closed (e.g., limited ventilation).

An example of a shot specific assumption is one where a ventilation system remains operational after the weapon hit. For example, this situation could occur if a well deck and/or vital spaces are part of the PDA(F). Including the effects of forced ventilation systems could result in an increase in fire intensity, particularly for cases where the fire would be oxygen starved otherwise.

3.3 Characterization of Secondary Damage in the PDA(F)

3.3.1 Development of the Fire Model

A fire model is used to characterize the environment in PDA(F) spaces for each hit scenario. APDA(F) and BAPDA(F) spaces are not included in the fire model. Currently, the multi-compartment zone fire model used for this analysis is CFAST version 3.1.7 [10,11].

In developing the input for CFAST, the ventilation conditions must be defined. These conditions include those provided by natural and forced ventilation. Natural ventilation may be provided by holes in the skin of the ship (resulting from the weapon hit) and openings between PDA(F) compartments. At a minimum, oxygen for combustion is provided naturally through any openings to weather that result from the weapon hit. Forced ventilation may be provided in vital spaces where ventilation is not secured under material condition ZEBRA.

Another consideration for the model input is the fuel load in each space. The types of fuel consist of unspent missile propellant, Class A material and Class B fuel. Examples of Class A material include paper products found in storerooms and offices, electrical cable insulation, pipe insulation and bedding in berthing spaces. Class B fuels may be introduced by JP-5 (or equivalent) fuel storage tanks that are breached or damage to fuel lines. The following assumptions are used for characterizing the fires in these spaces:

- The fuel load is evenly distributed through the compartment;
- Trunks, voids and enclosed ladders do not participate in fire spread;
- In general, passageways do not have concentrated fuel loads except possibly cabling and pipe insulation. For passageways that serve as companionways or ladderways, there is no appreciable fuel load and fire cannot spread to or from the space. For long passageways (either athwartship or fore-to-aft), cabling and pipe insulation is installed in the overhead. Fire cannot spread from below to these spaces but can spread from adjacent compartments. In addition, once a fire is established in the overhead of these passageways, fire can spread to adjacent compartments or the compartment(s) above; and
- It is assumed that the doors to washrooms, water closets and showers (WR/WC/SH) that serve living areas are open when a fire begins. These areas will become involved in the fire simultaneously with the contiguous space; however, any resulting fire is likely to be very limited given the low fuel loads in

washroom spaces. Since WR/WC/SH areas typically do not have a substantial fuel load associated with them, it is assumed that they do not propagate fire spread.

For the initial CFAST run, only the fuel load in PDA(F) compartments is considered. It is assumed that fires ignite in all PDA(F) compartments that are intimate with the compartment containing the burst point and have available fuel at the time of the weapon detonation. This is a very aggressive assumption. Since specific details about the fuel loading are not usually available, fire growth rates associated with the type of materials expected in the spaces are used for these typical materials. More specifically, it is assumed that the fires follow “t squared” fire growth curves. This type of fire growth curve is represented by Equation 1:

$$\dot{Q} = \alpha t^2 \quad (1)$$

where \dot{Q} is the heat release rate of the fire (kW), α is the fire growth constant typically associated with the type of materials in the space (kW/s²) and t is the length of time the fire has burned (s).

A medium fire growth rate ($\alpha = 0.0117 \text{ kW/s}^2$) is used to represent Class A materials. This value was adopted after analysis of potential fire threats [12] and was validated during a weapons effects test (WET) conducted on the ex-USS *Dale* (CG-19) [13]. An ultra-fast fire growth rate ($\alpha = 0.1876 \text{ kW/s}^2$) is used to represent Class B pool fires involving JP-5 or equivalent diesel fuel [14].

3.3.2 Interpretation of Fire Modeling Results

The results from the fire modeling are used to predict the temperatures, interface heights (demarcation between smoke and relatively smoke free zones) and smoke levels in PDA(F) compartments. The temperature data are used to determine when or if fire will spread to these spaces. The interface height and smoke density data, in addition to the temperature data, are used to determine how tenable these compartments would be for protected and unprotected personnel. The criteria used for tenability are described in Section 3.4. This information is the

most basic output provided by the fire model. It has been validated and verified extensively [15-19].

3.4 Fire and Smoke Spread within the PDA(F)

Fire may spread to compartments within the PDA(F) via either hot gases passing through an open vent or heating of an intact boundary (bulkhead or deck). In this situation, fires resulting from the weapon detonation in the immediate vicinity of the burst point would spread to other compartments within the PDA(F). Both modes of fire spread are examined when evaluating fire spread to these PDA(F) compartments to determine which mode results in a faster (more conservative) fire spread time.

3.4.1 Fire Spread Through Vents

Fire spread through vents that connect compartments within the PDA(F) may result from several different scenarios. The highest probability of spreading fire occurs when a PDA(F) compartment reaches flashover. In this situation, hot gases that are in excess of 500 °C (932 °F) will flow into the adjacent space resulting in a radiant heat flux exposure of at least 20 kW/m². These fluxes exceed the critical radiant heat flux for piloted ignition of wood and select plastic materials [20]. The configuration or orientation of the fuel in vent connected spaces will not affect how readily it is ignited.

Another ignition scenario occurs when the fire is located in close proximity to the door, hatch or vent opening. The radiation from the flame can pass through the opening and ignite combustible materials in the adjacent space. In order to achieve ignition, the exposure must exceed the critical ignition heat flux associated with the combustible material. Critical ignition heat fluxes can be as low as 10-15 kW/m² [21]. This ignition mechanism is difficult to apply in a typical TSS/BDRA since it is dependent on the relative location and geometry of both the fire and the target fuel source.

The final scenario results from convective heating produced by hot gases (below 500 °C (932 °F)) flowing into the adjacent compartment. These hot gases can potentially heat combustibles in the vent connected PDF(F) compartments to their auto-ignition temperature.

The presence of glowing embers or firebrands may cause ignition more quickly. The auto-ignition temperature of materials can be measured through the use of the Setchkin Furnace [22]. The standardized procedure for measuring these temperatures, ASTM D 1929 [23], has been used for a wide range of materials. Review of published test data show that paper will ignite at approximately 230 °C (446 °F) and various polymers will ignite between 330-450 °C (626-842 °F) [24, 25].

Based on the review of these potential ignition scenarios, it is conservatively assumed that ignition via hot gases will occur in a PDA(F) compartment when the accumulated fire gas temperatures reach 230 °C (446 °F) in that adjacent space.

3.4.2 Fire Spread through Intact Boundaries

Fire spread within the PDA(F) may also occur via heat transfer through the thermally thin steel bulkheads [24, 26-28]. This scenario occurs globally during post flashover fires. It could also occur locally with smaller fires if the burning material is in close proximity to the boundary. This would be considered fire spread across an unbreached boundary.

When flames impinge directly on a steel boundary, the temperature of the boundary will increase until it begins to glow red at approximately 350 °C (572 °F). Depending on the heat source, the temperatures could reach values as high as 650 °C (1202 °F). The boundary serves as a fairly efficient radiant heat source that will increase the temperature of nearby objects significantly [20]. The amount of energy that is transferred through a bare steel boundary resulting from direct flame impingement can approach 50 kW/m² [20]. This energy consists of both convective (~50%) and radiative (~50%) components. As shown in Figure 3, the worst case heat flux exposures decrease from 25 kW/m² at the boundary surface to approximately 1.0 kW/m² at a distance of ten meters away from the boundary. As points of reference, spontaneous ignition of combustible materials typically occurs around 20 kW/m², piloted ignition of combustibles occurs around 10 kW/m² and bare skin begins to blister for short exposures (less than one minute) around 5 kW/m² [21, 29, 30]. Under worst case conditions, spontaneous ignition can occur as far away as 0.8 m (2.5 ft) away from the boundary.

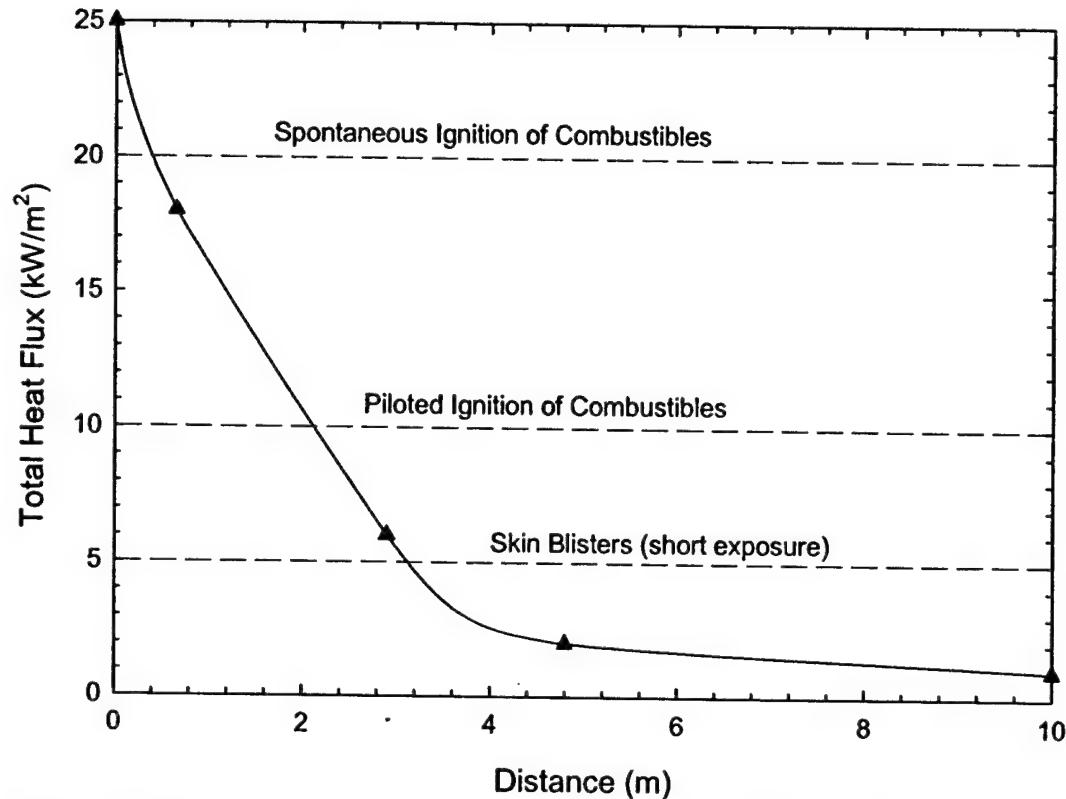


Figure 3. Worst case heat flux exposures as a function of distance from a bulkhead or deck

For aluminum the heat transfer would be difficult and failure of the bulkhead could be expected under extreme conditions. The melting point of pure aluminum is 660 °C while aluminum alloys can melt around 500 °C [31]. Also aluminum loses one half of its structural strength at 330 °C. There is a significant difference for composites. As composites are insulators, the heat transfer would be significantly delayed. It should be kept in mind that most composites in general use today could become fuels with time/temperature insult. This would eventually result in a breached boundary.

Ignition can also occur when combustible materials are in contact with the hot boundary and the temperature exceeds the auto-ignition temperature of the material (230 °C (446 °F)). Although both mechanisms (contact or radiant heating) are realistic scenarios, fire spread will occur the most quickly with contact heating. However, this type of scenario is difficult to model

without knowledge of the fuel load distribution. Even in cases where the normal distribution is known, it is likely that items will be relocated as a result of the impact from the weapon hit. As a result, it was assumed that smaller, pre-flashover fires could cause ignition of ordinary combustibles due to thermal penetration of steel boundaries on the same time scale as post flashover fires.

In order to determine the amount of time, t_{spread} , that is required to spread fire across a boundary (e.g., heat it to 230 °C (446 °F)), Equation 2 is used:

$$t_{spread} = t_{growth} + t_{penetration} \quad (2)$$

where t_{growth} is the time for the fire to reach flashover in the initiating compartment and $t_{penetration}$ is the time required to transfer heat through the boundary. All times are measured in minutes. This equation applies to both vertical and horizontal spread independent of the fire source (post flashover or localized heating).

The fire growth time (t_{growth}) is a function of the fuel loading and configuration in the compartment, the oxygen available for combustion (ventilation) and the size of the compartment. Since the fuel loading and configuration is unknown at the time of the hit, it is assumed that there is adequate fuel to sustain a fully developed fire for the duration of this simulation.

The fire growth times were determined by modeling a range of compartment sizes using CFAST. The compartment footprints (A_f) ranged from 9.3 to 464.5 m² (100 to 5000 ft²). The compartment height was taken as 3.0 m (10 ft), a typical deck-to-deck height. It was assumed that the fire is unconstrained (i.e., ample oxygen to support combustion) in a closed compartment. In addition, a Class A fire growth curve was used ($\alpha = 0.0117 \text{ kW/sec}^2$). The Class A growth curve was selected since most shipboard spaces will contain Class A fuels as opposed to Class B fuels. The growth time was defined as the number of minutes required for the upper layer temperature to reach 500 °C (932 °F).

The fire growth times that were conservatively developed based on the fire modeling results are summarized in Table 1. It should be noted that the growth time for vertical spread from any compartment and horizontal spread from any PDA(F) compartment is 5 minutes, regardless of the compartment size. Since fires can quickly expose the overhead to high heat fluxes, vertical fire spread to taller spaces (multi-deck) may be handled on a case-by-case basis (i.e., hit specific assumption).

Table 1. Fire growth times (T_{growth}) for a range of compartment footprints

Spread Direction	Compartment Footprint (A_f) [m^2 (ft^2)]	T_{growth} (minutes)
Vertical	any compartment	5
Horizontal	any PDA(F) compartment	5
Horizontal	$0 (0) < A_f < 93 (1000)$	5
Horizontal	$93 (1000) \leq A_f < 139 (1500)$	7
Horizontal	$139 (1500) \leq A_f < 186 (2000)$	9
Horizontal	$186 (2000) \leq A_f < 232 (2500)$	11
Horizontal	$232 (2500) \leq A_f < 279 (3000)$	13
Horizontal	$279 (3000) \leq A_f < 325 (3500)$	15
Horizontal	$325 (3500) \leq A_f < 372 (4000)$	17
Horizontal	$372 (4000) \leq A_f < 418 (4500)$	19
Horizontal	$418 (4500) \leq A_f < 465 (5000)$	21
Horizontal	$A_f \geq 465 (5000)$	23

The thermal penetration time ($t_{penetration}$) was determined using the finite difference heat conduction model – HEATING (Version 7.3 [32]). Steel plate thicknesses between 12.7 mm (0.5 in.) and 101.6 mm (4.0 in.) were modeled. The results in Table 2 are based on the following conservative boundary conditions applied to the exposed steel surface: the surface temperature was set at 1000 °C (1832 °F), an emissivity of 0.7 was used and a convective heat transfer coefficient of 10 W/m²K was imposed. Based on numerous tests on *Shadwell*, a steel

temperature of 600°C is rare as is a flame temperature above 800 °C in ship compartments. The penetration time was defined as the number of minutes required to heat the unexposed surface to 230 °C (446 °F) by direct flame impingement on the opposite side. The Verification and Validation (V&V) of HEATING has been accomplished previously and is being summarized as part of the V&V process of another ship platform VAR. Results from this analysis are summarized in Table 2.

Table 2. Penetration times ($t_{penetration}$) for various plate thicknesses

Plate Thickness (P_t) [mm (in.)]	$t_{penetration}$ (minutes)
$P_t < 12.6$ (0.49)	1
12.7 (0.5) $\leq P_t < 19.0$ (0.74)	2
19.1 (0.75) $\leq P_t < 25.3$ (0.99)	3
25.4 (1.0) $\leq P_t < 31.7$ (1.24)	4
31.8 (1.25) $\leq P_t < 50.7$ (1.99)	5
50.8 (2.0) $\leq P_t < 76.1$ (2.99)	7
76.2 (3.0) $\leq P_t < 101.5$ (3.99)	11
$P_t = 101.6$ (4.0)	15

It should be recognized that the times shown in Table 2 are conservative/generic guidelines. They do not account for the effects of insulation or bulkhead/deck treatments which could significantly impede thermal penetration or prevent it altogether.

In summary, the amount of time required to spread fire through an intact boundary is determined by identifying the fire growth time and the thermal penetration time. The fire growth time is a function of the type of compartment (PDA(F) as compared to APDA(F) or BAPDA(F)) and/or compartment size (Table 1). The thermal penetration time is a function of the bulkhead or deck thickness (Table 2).

3.4.3 Assessment of Tenability

The tenability guidelines are divided into two categories: those for unprotected personnel and those for protected personnel (DC parties). It is assumed that protected personnel are outfitted with self-contained breathing apparatus (SCBAs) and firefighting ensembles (FFEs).

For unprotected personnel, conditions are considered untenable when the smoke is too hot to breathe or the visibility is too poor for evacuation activities. Untenable conditions are assumed to occur when a smoke layer is below 1.5 m (4.9 ft), combined with one or both of the following conditions [33]:

- Upper layer temperature $> 100^{\circ}\text{C}$ (212°F) and/or
- Visibility < 4 m (13 ft) for transported troops and < 1.7 m (5.6 ft) for unprotected ship personnel.

The smoke layer height of 1.5 m (5.0 ft) is significant because it is below the normal head height. This condition would result in the potential exposure of standing personnel to hot gases or reduced visibility. The temperature criteria was chosen based on the fact that personnel exposed to gases above 100°C (212°F) will experience pain and potential damage to their respiratory tract [34-36]. Burning of the respiratory tract can result in severe injury or incapacitation for any person forced to breathe these gases. The failure criteria of 100°C is conservative as compared to the human tolerance temperatures in the NSTM 555, which indicate incapacitation after an exposure for 5 minutes to gases of 149°C (300°F) and incapacitation after an exposure for 35 minutes to gases of 93°C (199°F) [21].

Visibility throughout the primary and secondary damage compartments is important from a life safety/egress standpoint. Successful egress is contingent upon personnel being able to locate the ladders, hatches and the appropriate egress paths. Visibility degradation relates to the ability of occupants to egress through areas that may be smoke logged. It is possible for personnel to become disoriented in the event the visibility becomes significantly reduced. The minimum visibility for egress activities is dependent upon the occupant. Since some ships may

transport troops that are not familiar with the ship's layout, more visibility would be required for egress activities than for ship personnel. This difference is accounted for by assuming a visibility criterion for ship personnel that corresponds to the more generous limit identified in the literature of 1.7 m (5.6 ft) [33]. This value corresponds to data that indicate it is the point where egressing occupants will decrease their walking speed significantly [37]. A more stringent criterion of 4.0 m (13 ft) visibility is used for troops that are being transported [33, 38, 39].

Failure criteria for protected personnel were established based on the conditions that would not permit necessary firefighting operations to proceed. A smoke temperature of 200 °C (326 °F) was conservatively chosen. Certainly, firefighters in FFEs could tolerate higher exposure temperatures for short durations. Tests have shown that a firefighter in an FFE may be forced to abandon a space after 5 minutes when the temperatures are approximately 260 °C (500 °F) at head level. This translates to a temperature gradient in the compartment of 163 °C (325 °F) at waist level and 63 °C (145 °F) at knee level. Well-trained Navy fire fighters that have been through the ex-USS *Shadwell* experience can withstand hot gas layers above these and at higher temperatures [40]. For the purpose of evaluating the fire modeling results, it was assumed that a layer interface height of 0.6 m (2.0 ft) and an upper layer temperature of 200 °C (392 °F) constitute untenable conditions for protected personnel.

3.5 Characterization of Secondary Damage to APDA(F) and BAPDA(F) Spaces

Fire spread from APDA(F) spaces and BAPDA(F) spaces occurs via heat transfer through intact bulkheads and decks. This mode of fire spread is the most predominant since these spaces normally do not have vent connections to the spaces with fires. As a result, the methodology described in 3.4.2 is used to characterize secondary damage to these spaces. The tenability of these spaces is not assessed. Rather, it is assumed that they are untenable for unprotected personnel as soon as fire spreads to them. The analysis continues until the fire spread times are larger than the length of time that is specified for the analysis. For example, if secondary damage is only a concern for 30 minutes after the weapon hit, fire spread times longer than 30 minutes are not considered.

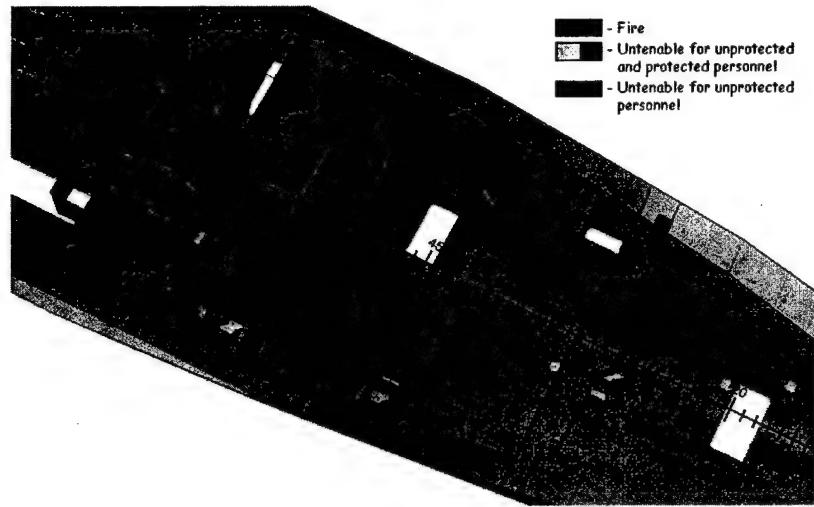
In many situations, the use of these prescriptive rules is conservative since it is assumed that there is an unlimited amount of fuel and air available in each compartment. In the event that there is a small amount of fuel in the compartment or the compartment is closed, fire spread may be delayed or may not occur at all.

3.6 Documentation of Secondary Damage Estimates

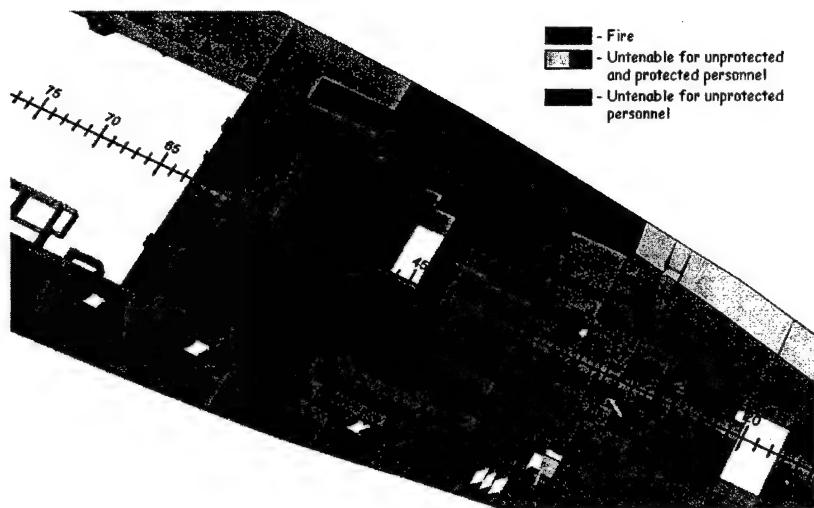
The secondary damage for a particular weapon hit is reported in a snapshot format. These snapshots show which spaces contain fires at particular points in time. In addition, the tenability for PDA(F) spaces is shown. Fire suppression effects are shown in situations where suppression systems are considered. Figures 4-6 show examples of these snapshots 5, 10 and 15 minutes, respectively, after the hypothetical weapon hit represented in Figures 1 and 2. Compartments containing fire are marked in red. Compartments that are not tenable for unprotected personnel are designated with blue. Those compartments that are untenable for all personnel (unprotected and protected) are shown in yellow. It should be noted that the rules-based fire spread framework was used for the development of these examples. These results would be contingent on the incorporation of CFAST results.

4.0 SUMMARY

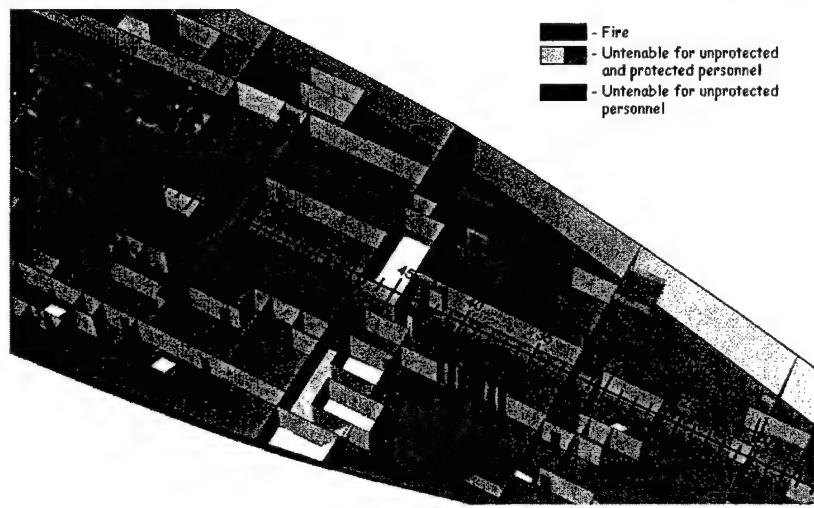
A methodology has been developed as part of a congressionally mandated LFT&E programs to predict smoke and fire spread after a weapon hit. The objective of the current methodology is to identify specific weaknesses and/or shortcomings that might increase survivability.



Second Deck

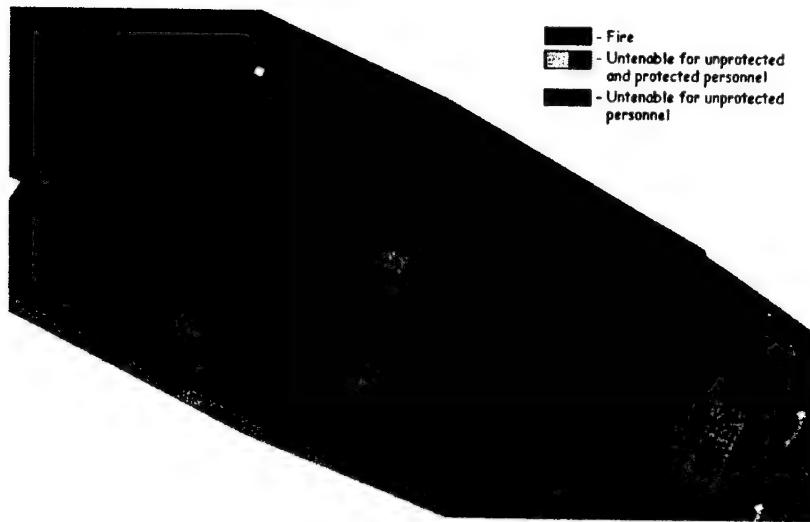


Third Deck

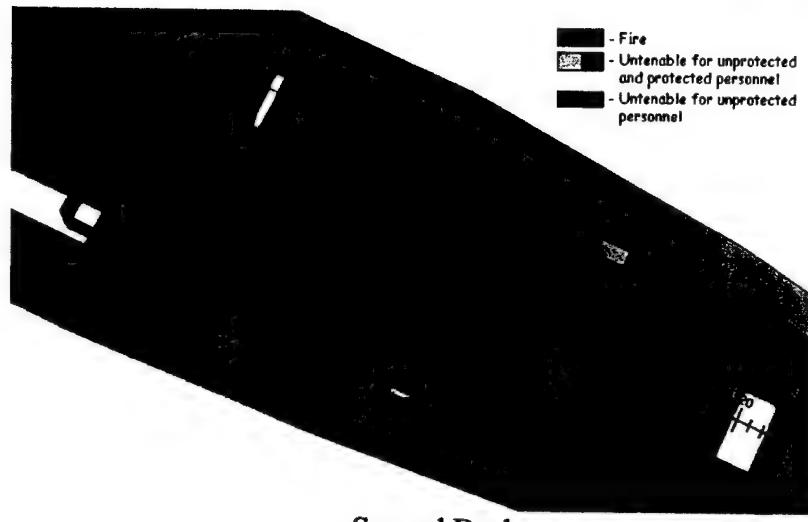


First Platform

Figure 4. Example of secondary damage 5 minutes after hypothetical weapon hit

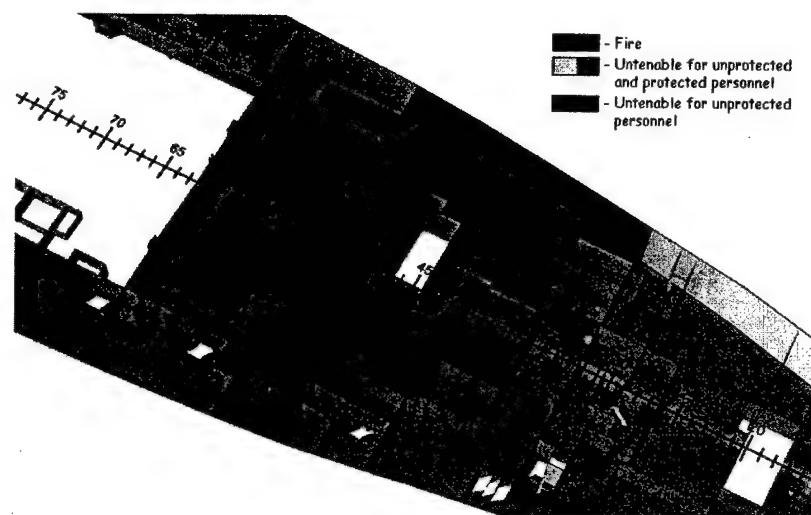


Main Deck

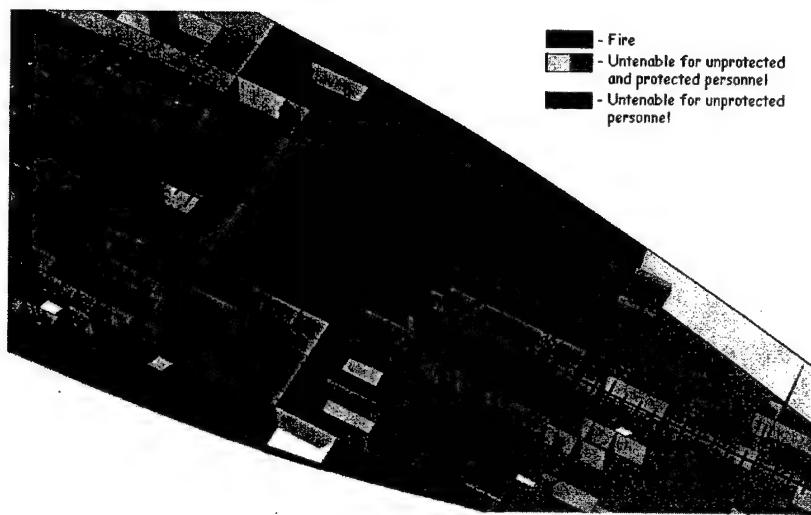


Second Deck

Figure 5a. Example of secondary damage 10 minutes after hypothetical weapon hit

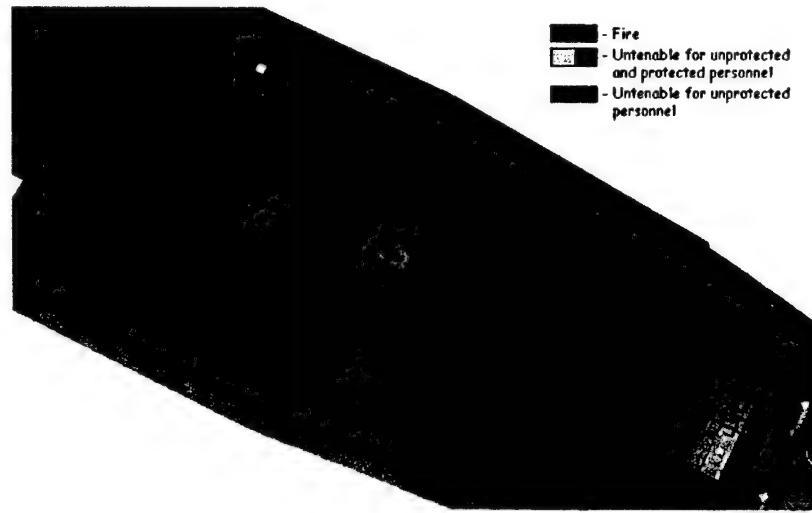


Third Deck

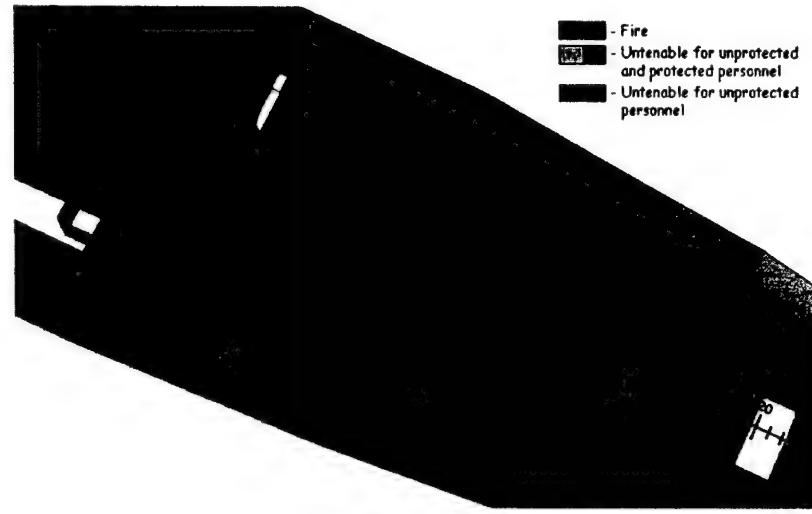


First Platform

Figure 5b. Example of secondary damage 10 minutes after hypothetical weapon hit (continued)

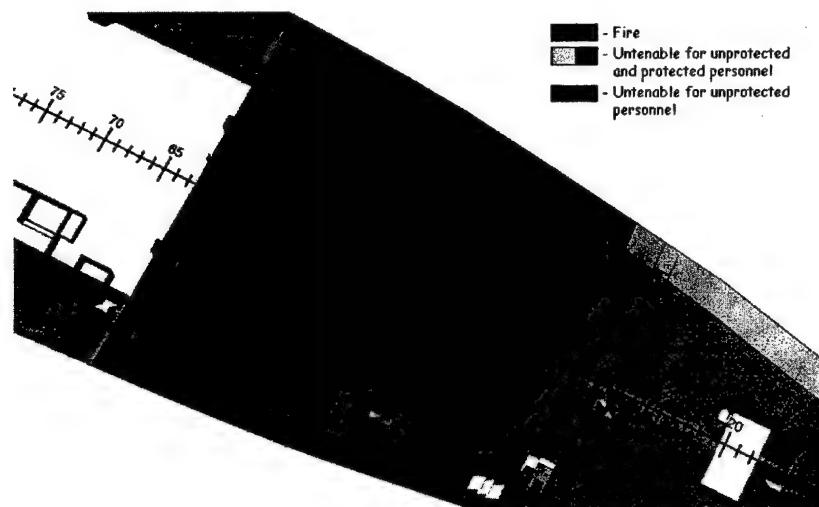


Main Deck

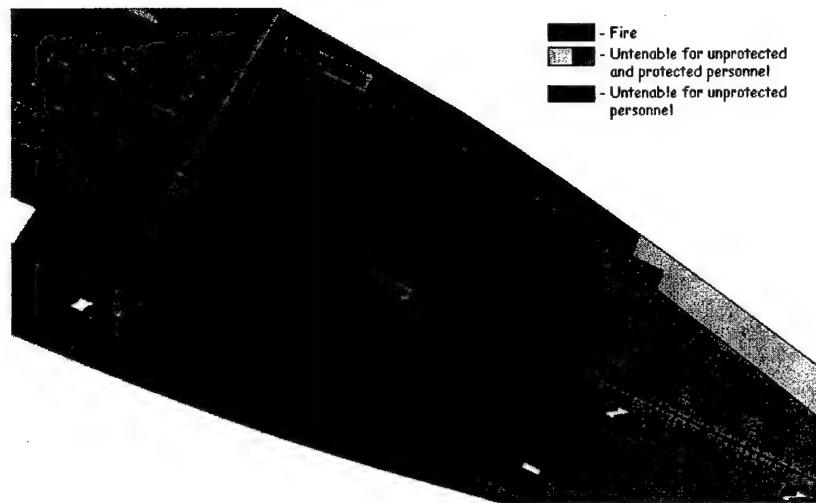


Second Deck

Figure 6a. Example of secondary damage 15 minutes after hypothetical weapon hit



Third Deck



First Platform

Figure 6b. Example of secondary damage 15 minutes after hypothetical weapon hit (continued)

The methodology is summarized in the flowchart shown in Figure 7. Figure 8 is a flowchart for tenability. The process involves modeling PDA(F) compartments with the multi-compartment zone fire model CFAST. The use of CFAST allows for a more complete characterization of these compartments. The output from CFAST is used to predict fire spread times and assess tenability conditions. Fire spread beyond these compartments to APDA(F) and BAPDA(F) compartments is predicted using a conservative set of prescriptive rules.

5.0 FUTURE DEVELOPMENTS

The methodology described in this report is currently being applied in the VAR 3 process for the LPD 17 platform detailed design. Any further developments or improvements in the methodology will be documented and reflected in a future revision of this report. Separate efforts are underway to develop a network fire model [41]. The network fire model would provide a physics based model that could quickly assess fire and smoke spread for ship platforms. Plans also include accounting for fire detection and suppression effects. This type of model would provide better far field secondary damage characterization capabilities. It is unclear if the network fire model will replace the current methodology or if it will be used in conjunction with the method or portions of the method described in this report. Significant changes in direction for predicting secondary damage associated with LFT&E efforts will be documented in future reports.

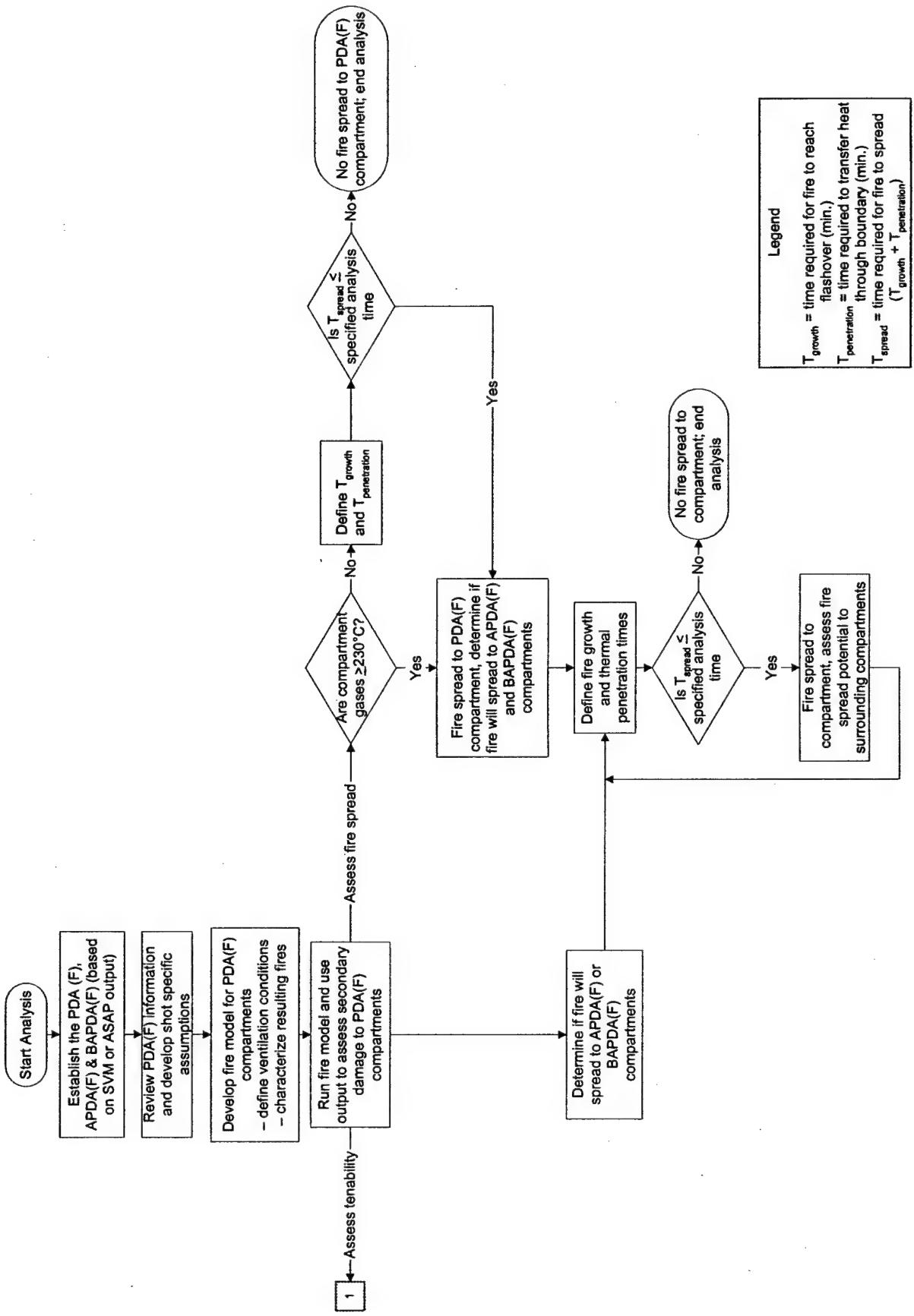


Figure 7. Flowchart for fire and smoke spread methodology

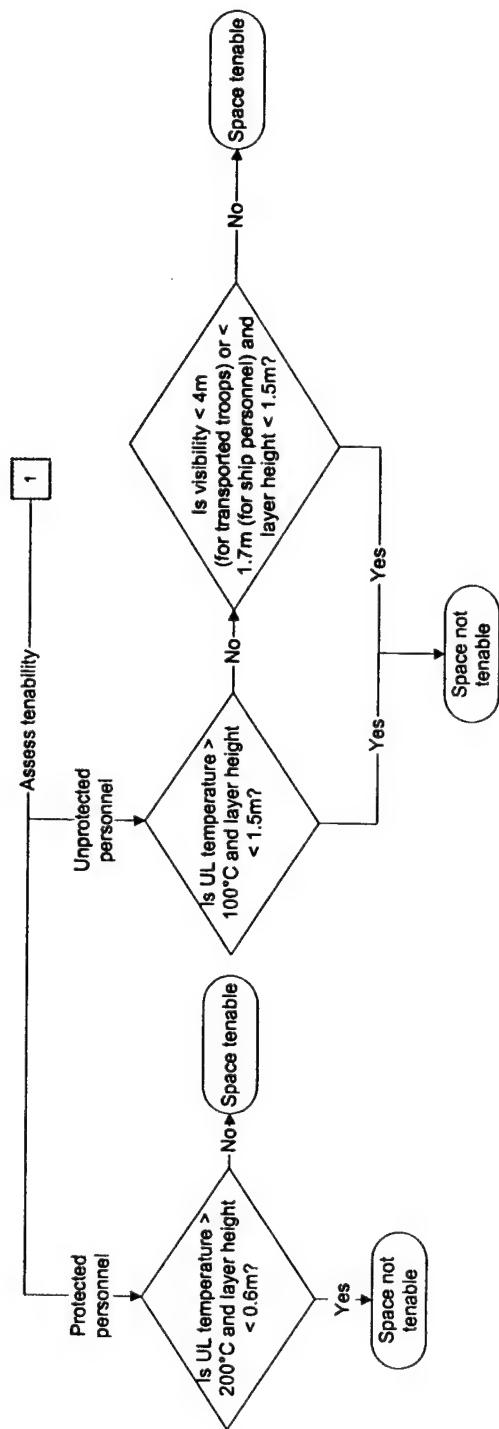


Figure 8. Flowchart for fire and smoke spread methodology for tenability

6.0 REFERENCES

1. Williams, F.W., Scheffey, J.L., Tatem, P.A., and DiNenno, P.J., "Review of Fire Spread Parameters for Total Ship Survivability/Fleet Training (TSS/FT) Fire Spread Model, NRL Ltr Rpt Ser 6180-107, 22 April 1992.
2. White, D.A., Rhodes, B.T., DiNenno, P.J., Tatem, P.A., and Kay, D., "Smoke and Fire Spread Evaluations: LPD-17 Amphibious Transport Dock Ship Total Ship Survivability and Battle Damage Repair Assessments (U)," NRL/MR/6180-97-7985, 30 September 1997 (Confidential).
3. Back, G.G., Darwin, R.L., Hopkins, D., Mack, E.C., Scheffey, J.L., White, D.A., Tatem, P.A., Williams, F.W., and Hunstad, M., "CVNX1 Vulnerability Report (2) and Battle Damage Repair Assessment: Fire and Smoke Spread Evaluation (U)," NRL report in preparation, 18 March 2002 (Secret).
4. Luers, A.C., Gottuk, D.T., Pham, H.V., Scheffey, J.L., Wong, J.T., Downs, R., Runnerstrom, E., Farley, J.P., Williams, F.W., Tatem, P.A., Durkin, A., Nguyen, X., and Buchanan, J., "FY 2001 DC-ARM Final Demonstration Report," NRL/MR/6180-02-8623, 31 May 2002.
5. Peatross, M.J., Luers, A.C., Pham, H.V., Scheffey, J.L., Wong, J.T., Farley, J.P., Williams, F.W., Tatem, P.A., Nguyen, X., and Rose-Pehrsson, S.L., "Results of the FY 2000 DC-ARM Demonstration," NRL Ltr Rpt Ser 6180/0029, 07 February 2001.
6. Parker, A.P., Strehlen, B.D., Scheffey, J.L., Wong, J.T., Darwin, R.L., Pham, H., Runnerstrom, E., Lestina, T., Downs, R., Bradley, M., Toomey, T.A., Farley, J.P., Williams, F.W. and Tatem, P.A., "Results of 1998 DC-ARM/ISFG Demonstration Tests," NRL Ltr Rpt Ser 6180/0032, March 12, 1999.
7. Back, G.G., Scheffey, J.L. and Williams, F.W., "Spruance Class Weapon Effects Test – Fire Spread Evaluation: Preliminary Report," NRL Ltr Rpt 6180/0584, December 26, 2002
8. "Ship Vulnerability Model Program Maintenance/Analyst Manual (U) Volume I. Simulation Model Part 1," Tom Carroll Associates, November 1985.
9. Adamchak, J., *et al*, "Advanced Survivability Assessment Program Verification and Validation Plan (U)," April 2002.
10. Peacock, R.D., Reneke, P.A., Jones, W.W., Bukowski, R.W., and Forney, G.P., "A User's Guide for FAST: Engineering Tools for Estimating Fire Spread and Smoke Transport," Special Publication 921 2000 Edition, National Institute of Standards and Technology, Gaithersburg, MD, January 2000.

11. Peacock, R.D., Forney, G.F., Reneke, P., and Jones, W.W., "CFAST, the Consolidated Model of Fire Growth and Smoke Transport, Version 4.0.1" NIST Technical Note 1431, National Institute of Standards and Technology, Gaithersburg, MD, January 2000.
12. Back, G.G., Iqbal, N., William, F.W., and Scheffey, J.L., "Potential Compartment Fire Growth Curve Resulting from a Missile Hit," NRL Ltr Rpt 6180/0526, 27 October 1998.
13. Back G.G., Darwin, R.L. and Williams, F.W., "Weapons Effects Test (EX-USS DALE [CG-19]) Compartment Fire Evaluation (U)," NRL Ltr Rpt 6180/0022, 04 February 2002 (Confidential).
14. Evans, D.D., "Ceiling Jet Flows," *The Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering*, 2nd Edition, National Association of Fire Protection Engineers, Quincy, MA, 1995.
15. Bailey, J.L. and Tatem, P.A., "Validation of Fire/Smoke Spread Model (CFAST) Using ex-USS *Shadwell* Internal Ship Conflagration Control (ISCC) Fire Tests," NRL Memorandum Report 6180-05-7781, 30 September 1995.
16. Bailey, J.L. and Tatem, P.A., "Validation of Fire/Smoke Spread Model (CFAST) Using ex-USS *Shadwell* Smoke Ejection System Fire Tests," NRL Ltr Rpt, 6180/0007.2, 24 January 1994.
17. Hoover, J.B., Bailey, J.L. and Tatem, P.A., "Validation of Gas Phase Absorbance Algorithm in the Consolidated Fire Growth and Smoke Transport CFAST Model," NRL Ltr Rpt, 6180/0020, 8 March 1996.
18. Nelson, H.E., and Deal, S. (1991), "Comparing Compartment Fires with Compartment Fire Models," *Fire Safety Sciences-Proceedings of the Third International Symposium*, Elsevier, NY, pp. 719-728.
19. Peacock, R.D., Jones, W.W., and Bukowski, R.W., "Verification of a Model for Fire and Smoke Transport," *Fire Safety Journal*, 21, 1993, pp. 89-129.
20. Back, G.G., Darwin, R.L., and Beyler C.L., "An Evaluation of the Cooling Capabilities of Water Spray Systems in Cargo Holds," Hughes Associates Report, 10 February 2000.
21. Department of the Navy "Naval Ships' Technical Manual Chapter 555-Volume 1, Surface Ship Firefighting," S9086-S3-STM-010/CH-555V1R9, 1 December 2001.
22. Setchkin, N.P., *National Bureau of Standards Journal of Research*, National Bureau of Standards, Gaithersburg, MD, 1949.
23. American Society of Testing and Materials, "ASTM D1929, Standard Test Method for Ignition Properties of Plastics," Philadelphia, PA, 1983.

24. Darwin, R.L., Leonard, J.T., and Scheffey, J.L., "Fire Spread by Heat Transmission Through Steel Bulkheads and Decks," *Proceedings of IMAS Conference on Fire Safety on Ship*, Institute of Marine Engineers, London, England, May 1994.
25. Drysdale, D., "An Introduction to Fire Dynamics," Second Edition, John Wiley & Sons, Chichester, 1999.
26. Back, G., Beyler, C., DiNenno, P., and Tatem, P., "Wall Incident Heat Flux Distributions Resulting from an Adjacent Fire," *Fire Safety Science-Proceedings of the Fourth International Symposium*, 1994, pp. 241-252.
27. Back, G.G., Leonard, J.T., Fulper, C.R., Darwin, R.L., Scheffey, J.L., Willard, R.L., DiNenno, P.J., Steel, J.S., Ouellette, R.J., and Beyler, C.L., "Post-flashover Fires in Simulated Shipboard Compartments: Phase I – Small Scale Studies," NRL/MR/6180--9886, 3 September 1991.
28. Scheffey, J.L., Hill, S.A., Toomey, T.A., Leonard, J.T., Williams, F.W., Smith, D.E., and Darwin, R.L., "Post-flashover Fires in Shipboard Compartments Aboard ex-USS *Shadwell*: Phase V Fire Dynamics," NRL/FR/6180-99-9902, 31 May 1999.
29. Vegthe, J.J., "Human Exposure to High Radiant Environments," *Aerospace Medicine*, Vol. 44, pp. 1147-1157, 1973.
30. Stoll, A.M. and Chianta, M.A., "Evaluation of Thermal Protection," *Aerospace Medicine*, Vol. 11, pp. 1232-1238, 1989.
31. White, F.M., "Heat Transfer," Addison-Wesley Publishing Company, Inc., Reading Massachusetts, 1984.
32. Oak Ridge National Laboratory, "HEATING," Multidimensional Finite-Difference Heat Conduction Analysis Code System Version 7.3, ORNL, Oak Ridge, Tennessee, 1999.
33. Peacock, R.D., Jones, W.W., Bukowski, R.W., and Forney, C.L., "Technical Reference Guide for HAZARD I Fire Hazard Assessment Method, Version 1.1," NIST Handbook 146, Volume II, National Institute of Standards and Technology, Gaithersburg, MD, June 1991.
34. Purser, D.A., "Toxicity Assessment of Combustion Products," *The Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering*, 2nd Edition, National Association of Fire Protection Engineers, Quincy, MA, 1995.
35. Bryan, J.L., "Damageability of Buildings, Contents and Personnel from Exposure to Fire," *Fire Safety Journal*, 11, 1986, pp. 15-31.
36. Vegthe, J.H., "Design Criteria for Fire Fighters' Protective Clothing," Jansville Apparel, 1st Edition, September 1981.

37. Jin, T., "Visibility Through Fire Smoke," Report of Fire Research Institute of Japan, **2** (33), 1971, pp. 12-18.
38. Budnick, E.K., "Mobile Home Living Room Fire Studies: The Role of Interior Finish," NBSIR 78-1530, National Bureau of Standards, Gaithersburg, MD, September 1978.
39. Malhotra, H.L., "Movement of Smoke on Escape Routes, Part 1 – Instrumentation and Effect of Smoke on Visibility," Joint Fire Research Organization, Borehamwood Fire Research Note 651, England, January 1967, p. 21.
40. Scheffey, J.L., Jonas, L.A., Toomey, T.A., Byrd, R., and Williams, F.W., "Analysis of Quick Response Fire Fighting Equipment on Submarines – Phase II, Full Scale Doctrine and Tactics Tests," NRL Memorandum Report 6632, 10 July 1990.
41. Floyd, J., Scheffey, J., Haupt, T., Al Habbash, H., Hodge, B., Norton, O., Williams, F., and Tatem, P., "Requirements for a Shipboard, Network Fire Model," NRL Ltr Rpt 6180/0469, January 23, 2003.